GALLIUM ARSENIDE MICROMECHANICS
A Comparison to Silicon and Quartz

Klas Hjort
School of Engineering, Uppsala University, Box 534
S-751 21 Uppsala, Sweden fax. +46 18 555095

Abstract

The review compares GaAs micromechanics to silicon and quartz. It is shown that in micromechanics, GaAs combines the advantages of both silicon and quart. Like silicon it is semiconducting and it is possible to do advanced micromachining in GaAs. Like quartz, it is piezoelectric and may have a very high bulk resistivity. Also, with GaAs come new possibilities in integrated optoelectronics, such as lasers and photodiodes. Inspite of a lower mechanical endurance, the strength of GaAs micromechanics is sufficient for most micromechanical applications. It is concluded that GaAs has a large unexploited potential in micromechanics.

Introduction

Micromechanics comprises the techniques of fabricating and using mechanical structures in the size range below that of traditional fine mechanics. To the mechanical technology micromechanics offers the same advantages and opportunities by miniaturization and batch fabrication as microelectronics gives the electronics.

In the last two decades, micromechanics has been an ever increasing area of technological impact. The earliest commercially successful application was the quartz tuning forks for frequency control in watches, but there are only a few other micromechanical devices realized in quartz. In most micromechanical applications silicon is used. Micromechanical silicon structures have today most of the world market in pressure sensors and air bag accelerometers.

Gallium arsenide (GaAs) and its compounds possess a number of materials parameters making them interesting for micromechanical applications. They are well known materials in optoelec- tronics, and high-frequency and high-speed electronics. For these applications most of the tools needed for micromechanics are already developed. Being piezoelectric, optoelectric, and semiconducting, GaAs should be able to be used with advantage in some sensor or actuator applications. Furthermore, GaAs is used in high-temperature electronics, enabling a wide temperature span for integrated sensors. This review aims from a materials science point of view to survey GaAs and its most well-developed ternary, the aluminum gallium arsenide ($Al_xGa_{1-x}As$), as micromechanical materials. Since there is no use to introduce a new material if the old ones are sufficient, it is necessary to compare GaAs with the two major micromechanical materials of today: silicon and quartz. Therefore this review.

Mechanical Properties

In this section, the micromechanical characteristics are presented for GaAs and AlGaAs, and are compared to those of silicon and quartz. Below, in Table 1 some relevant data are gathered for comparison. For more information on GaAs as a mechanical material, see [1].

Table 1. Micromechanical properties for GaAs, AlAs, silicon and quartz[a)]

	GaAs	AlAs	Silicon	Quartz
Crystal structure	zinc blende (43m)	zinc blende (43m)	diamond (m3m)	quartz (23)
Lattice constant , a [pm]	565.330	566.139	543.106	490.4
c				539.4
Density, ρ [g/cm^3]	5.3165	3.7290	2.3290	2.649
Melting point, T_M [°C]	1238	1740	1413	1710
Thermal expansion, α_{11} [ppm/K]	6.0	4.2	2.6	13.7
α_{33}				7.5
Thermal resistivity [Kcm/W]	2.27	1.1	0.64	8.1-15
Stiffness constants[GPa]				
c_{11}	118.8	120.2	165.6	86.8
c_{12}	53.8	57.0	63.98	7.04
c_{44}	59.4	58.9	79.51	58.2
c_{13}				11.91
c_{14}				-18.04
c_{33}				105.75
Hardness[b)], Hv(100)[GPa]	7	5	10	12
Toughness[b)], K_{Ic} [MPam$^{1/2}$]	0.44	1.7	0.9	—
Fracture strength, σ_f[c)] [GPa]	2.7	—	6.0	1.7

a) If not otherwise stated, the data are gathered from [2] for GaAs and AlAs, for silicon from [3], and for quartz f.rom [4]. Temperature and pressure dependent values are given for room temperature and 1 atm.

b) The hardness and fracture toughness values for GaAs and AlAs are taken from [5], for silicon from [6].

c) The *average* fracture strength value for GaAs is taken from [7], for silicon from [8], and for quartz from [9].

Structural Properties

As seen from Table 1, two structural comparisons may directly be done. Primarily, the lattice difference of GaAs and AlAs is very small, enabling good quality heterostructures of the alloys without high strains in the films. Secondly, the density of GaAs is nearly 60 % higher than the one of AlAs, and more than twice the densities of silicon and quartz. The density is of large importance for the mechanical behavior of devices in, e.g. acceleration and resonant applications.

One of the primary aspects in both mechanics and micromachining of monocrystalines are their crystal structures and the anisotropies they induce. Therefore this short reminder:

GaAs and AlAs, being crystals with the cubic zinc blende structure, have a crystal symmetry reminding of the elemental diamond structure of, e.g. silicon. The difference is that the two face-centered cubic (fcc) lattices, displaced a quarter of the lattice cube diagonal from each other, are occupied by different elements. That reduction in symmetry makes a dipole moment in the lattice diagonal direction <111>. In the case of GaAs, the electron cloud shift towards the arsenic atoms, resulting in, e.g., a non-vanishing piezoelectric coefficient; a fracture toughening of the {111} planes, yielding {110} as the primary cleavage planes; and that the eight {111} planes form pairs of "Ga-rich" and "As-rich" planes opposite to each other.

Quartz differs quite a lot from the others by belonging to the trigonal trapezohedral class, characterized by one axis of three-fold symmetry, and perpendicular to it three polar axes of two-fold symmetry separated 120° from each other. There are no center or plane of symmetry in the quartz structure.

Mechanical Endurance

GaAs wafers have been known to be very fragile, and consequently little attention has been shown to GaAs as a mechanical material. But being a brittle material GaAs will deform elastically until brittle fracture. The fracture strength (σ_f) is proportional to the material constant 'critical fracture toughness' (K_{Ic}), and limited by the largest stress concentration, i.e. often the largest defect. Consequently, if we reduce the mechanical active volumes the risk of a large defect is reduced and the chance to build a strong structure is risen.

The shape of a defect is of minor importance if the size of the defect is as small as comparable to the fracture process region [10]. For the strengths shown in Table 1 the defect sizes should be comparable with the sizes of process regions, even in these brittle materials. Therefore, we may assume that the fracture behavior of the defects and penny-shaped cracks with the same radius, c, are comparable. For a penny-shaped crack, the fracture strength is:

$$\sigma_f = K_{Ic} (\pi c)^{-1/2} \qquad (1)$$

Of course, this expression will only give a rough estimate of the possible fracture strength. It should be used to realize how large defect sizes can be accepted for a mechanical application, which in most cases is a diameter of less than 0.1 microns. Surface defects are often more severe, since they are higher stress concentrators and situated where the stress is the highest, e.g. when bending.

For silicon the surface condition is of absolute importance for the fracture strength in micromechanics [8]. One way to reduce the surface defects in silicon is to heal or eat them away by oxidizing the surface. This might also be possible in GaAs. But in GaAs, it has also been shown that the bulk arsenic precipitates are in sizes and densities of importance for the micromechanical strength [7]. Therefore, from a micromechanical point of view it is desirable to have the arsenic precipitates in a finer dispersion. Still, as seen from Table 1 GaAs micromechanics may be stronger than quartz micromechanics, and much stronger than the strength of ordinary construction steel (0.8 GPa). Even though just half as strong as silicon micromechanics, this is by any means sufficient for mechanical construction.

Though the fracture strengths may be sufficient, in some applications the ability to endure wear, thermal shock, and fatigue are of importance. In these situations, GaAs is inferior to silicon and quartz, having a lower hardness, a low thermal conductivity, less stable oxides, and environmentally enhanced fatigue in e.g. water. The lower hardness and fracture toughness makes the wear rate of GaAs much faster than that of silicon. It demands much less to scratch or grind GaAs, and the erosion rate with alumina sand is nearly one magnitude higher for GaAs than for silicon [6]. For AlAs the fracture toughness is so high that inspite of the low hardness, the material should have a better mechanical endurance than GaAs (provided the same defect sizes and densities). Chemically AlAs is rather reactive, and mechanical parts in contact with environment are not recommended. But with a higher mechanical endurance coming with higher aluminium contents, AlGaAs with less than 50 % aluminum contents may be a good compromise. Fatigue has not been shown for silicon wafers under normal condition, but for GaAs wafers environmental enhanced cracking in water, methanol and other highly dielectric media has been shown [11].

If very slow aging is a demand, e.g. in resonators for standard time, quartz is superior to the others. Quartz has a very small aging, being an oxide with nearly no movable atoms in the crystal. Silicon and GaAs have most often impurity atoms that will slowly diffuse in the crystal lattice, and will also oxidize slowly. To minimize the dimensional changes a preoxidation to a thick oxide is recomendable, lowering the rate of oxidation afterwards to a minimum, cf. [12].

In short, GaAs should not be in direct contact with a hostile environment but protected by some intermediate layers or encapsulations. This is of course what is done today with all sensors that allow it, and not a severe limitation for the use of GaAs micromechanics. We have to conclude that when it comes to mechanical endurance, GaAs is inferior to the others. Still, in most cases the endurance should be sufficient.

Elastic and thermal properties

GaAs and quartz are not as stiff as silicon, for worse or better depends on the application. The elastic modulus is about 30% lower for GaAs than for silicon, which for example means that a rod of otherwise the same dimensions needs an 11 % increase in thickness for the same bending stiffness. The resonance frequency is directly proportional to the elastic modulus.

The elastic behavior of a single crystalline material is anisotropic, and described by the stiffness matrix (c_{ij}). From

this tensor matrix, it is possible to calculate the elastic modulus (Young's modulus) and the Poisson's ratio by relatively simple means [13]. The elastic behavior of the anisotropic material is of importance in any mechanical application in sensors or actuators, and should be taken into account when constructing a new device. When simulating the elastic behavior of a more complex device, finite element modelling (FEM) is recommendable.

As seen from Table 1, the linear thermal expansion of GaAs is 6.0 ppm/K. From linear interpolation of known data on the thermal expansion for $Al_xGa_{1-x}As$, a linear relationship with the composition is suggested with 4.2 ppm/K for AlAs [2]. The standard deviation for the latter is as much as 0.4 ppm/K, so further work on the thermal expansion of AlGaAs alloys is needed. Stress measurements indicate an approximate expression for the internal strain (ε_i) in an epitaxial $Al_xGa_{1-x}As$ film on (100) GaAs to be [5]:

$$\varepsilon_i(x,\Delta T) = 1.4\ 10^{-6} \times \Delta T \quad (2)$$

with the temperature difference ΔT between the growth temperature and the final temperatur. The stress may then be easily calculated for, using Hook's law $\sigma = E\,\varepsilon$.

The change of elasticity with temperature change the output of most sensors and actuators. For example, the change in resonance frequency of a device follows directly the change of elasticity and dimension [14]. This is one main reason why quartz is used as a reference resonator with extremely low temperature dependence, since in some crystal directions the change of elasticity and dimension expel each others influence. In silicon and GaAs this is not possible [1].

Micromachining and Microprocessing

To the largest extent micromachining use the techniques used in batch fabrication of electronics. This review will only try to show some inherent processes for micromechanics. Thus, the processes common with the planar micro- and optoelectronics technologies will not be taken into account here. The literature of these subjects is vast, and has been reviewed elsewhere, e.g. [15,16].

Wet etching

GaAs is less stable than silicon, which in turn is not as stable as quartz. This may be seen in some common wet etchants for micromachining each material, as shown in Table 2. Chemically $Al_xGa_{1-x}As$ and GaAs differs quite a lot, resulting in good etch selectivities in some wet etchants. This is the most common way to make etch stops in the GaAs/AlGaAs system, e.g. for LED's. When it comes to easiness of wet etching, quartz is inferior to the others being chemically so stable.

Most of the micromechanics are etched anisotropically to give well-defined rims to the mechanically active parts. Since the materials differ quite much in crystal anisotropy, the etch anisotropies do so too:

Table 2. Common wet etchants for micromachining.

Etchant	Comments	Refs.
$KOH:H_2O_2:H_2O$	Silicon etchant. Gives shiny flat surfaces. May be used in electrochemical etching. Attacking SiO_2.	17-20
$EDP:H_2O_2:H_2O$	Silicon etchant. May be used instead of KOH in electrochemical etching. Etch not as precise, but with much less attack on SiO_2.	20,21
$HF:NH_4F:H_2O$	Quartz etchant. The etch ratios differ significantly with the etch conditions.	22,23
$1\%\ Br_2:CH_3OH$	Mirrorlike etched surfaces. Enhanced etching at mask edge. Low Br_2 more preferential. Deep etching significantly slower. Slowly attacking SiO_2.	24-26
$H_3PO_4:H_2O_2:CH_3OH$ or $:H_2O$	Shiny flat etch bottom, and highly reproducible etch rate. Well etched mesa slopes, the inverse mesa slopes less precise.	27,28
citric acid : $H_2O_2:H_2O$	GaAs:AlGaAs selectivity up to 100. Flat etched bottom.	29,30
$NH_3OH:H_2O_2:H_2O$	The mostly used selective etch, mayetch isotropically with etch selectivities up to 500 for GaAs:AlGaAs, depending much on conditions. Will get anisotropic etching at some concentrations. Builds up a porous surface layer that lowers the etch rate, if the pH is less than 9.6. The layer may be prevented using spray etching.	31-34
$HF:H_2O$	Gives enormous etch selectivities betweenGaAs and AlGaAs when aluminum contents higher than 50 %, and between phosphorous glass and silicon. Is used for sacrificial layer etching.	35,36

Quartz etches with high aspect ratios, and in some crystal directions it is possible to obtain parallel vertical etched sides by etching simultaneously from the top and bottom sides. This is nearly always used in the different micromachined quartz structures used for resonator and sensor applications. Unfortunatly, by these means it is not possible to obtain orthogonal etched sides, which to some extent complicates the construction and simulations of the mechanics.

Silicon when anisotropically etched has the (111) planes as the slowly etched planes. From this fact, it is simple to make mesa structures with orthogonal corners in (100) wafers, or to make parallel vertical etched sides in (110) wafers. With more advanced lithography together with precise etching it is possible to play with the different speed of etch planes and obtain flat etched walls of other orientations, e.g. vertical walls with orthogonal corners in (100) wafers [18-20].

Being a semiconductor, this enable different kinds of electrochemical etching [37-39]. In micromachining this is often used to produce thin layers in an otherwise thick body. In silicon the structures are often defined by diffused pn-junctions, giving a well-defined thickness over the whole wafer. For example, this is used to make membranes or suspending bridges for sensor applications such as pressure sensors and accelerometers.

As mentioned before, the same lack of symmetry in GaAs which for example gives the piezoelectric effect also gives different chemical properties to the two (111) planes, making parallel pairs "Ga-rich" or "As-rich" planes. In anisotropic etching the (111)As planes are etched much faster than the (111)Ga planes. A simplified argumentation gives the reason for this: In an (111)As plane, the surface layers is built up either of As atoms with three bonds to underlying atoms, or Ga atoms with one bond to an underlying atom. With just one bond and three valence electrons, the Ga layer is easily swept away. Also, the As planes are rather reactive, since there are two free valence electrons of each atom. Hence the relatively high etch rate. For an (111)Ga plane the etch rate slows down: When the surface plane is built up by As atoms it is easily etched away but with the next layer of Ga atoms the surface is less reactive, since the valence electrons are occupied in the bonds to lower layers.

By the same kind of argument as above the etch rate decreases as (110)>(111)As>(100)>(111)Ga, cf. [25]. For (100) wafers this gives the well-known mesa-etched side walls for one parallel set directed <110> and inverse mesa for side walls orthogonal to the former. Unfortunately, the inverse mesa shape is problematic when stopping against a membrane, since the not so well defined border to the etch pit bottom when etching deeply. Even if this is solved, there is a sharp stress-concentrating corner at the rim of the membrane which could be critical for the mechanical strength. To some extent this unfortunate situation might be dealt by equivalent means to those used in the advanced lithography micromachining in silicon. Here, a lot of work could be done.

Like silicon, GaAs may be electrochemically etched with good selectivities (Table 3). Also, being optoelectrically active, there are means of both photochemical and electrophotochemical etching. Here the highest etch selectivities have been reported, and for micromachining also more exotic etchings as laser assisted etching of very narrow via holes [40], or holographic etching of optical gratings [41] have been reported. More information about GaAs wet etchants may be found in, e.g. [42-46]

Table 3. Photo- and electrochemical etchant in GaAs

Etchant	Comments	Refs.
$HCl:H_2O$	Photoelectrochemical etch with selectivity n+:p+ above 15.000.	47
$NaOH:H_2O$	Anodic spray etch. High selectivity.	48
acetic glacial acid : perchlorid acid	Anodic etching. Selectivity (n+: implanted layer of 10^{11} cm^{-2} $^{20}Ne^+$) ~ several thousand.	49
$KOH:H_2O_2:H_2O$ or $H_2SO_4:H_2O_2:H_2O$	Cathodic etching. High selectivity between semi-insulating and p-doped. Better control when slowly etching.	50

We may summarize that GaAs has the largest variety of possibilities in wet etching for micromachining, but may be difficult to work with when well-defined rims are needed in membrane applications. Still, silicon has a large number of well-known wet etch techniques giving high quality etch rims and etch stops, and may therefore have at least the same usefulness in micromachining with wet etchants. Also in this aspect, quartz is inferior to the others.

Dry etching

In micromachining, dry etching is rarely used for deep etching. It is most often used to structurize thin layers in surface micro- machining, or to open up bulk etched membranes. Dry etching in micromachining is not differing from the commonly used techniques in microelectronics and optoelectronics. For further reading, the book [51] and the review [46] are recommended.

To compare the different materials, GaAs has the advantages that it is possible to selectively etch against $Al_xGa_{1-x}As$, and that crystal plane etching is realizable [51]. Dry etching of quartz is not often used in micromachining, but may be found in [52,53].

Sacrificial layer etching

The first laterally mobile polysilicon structures built-up with sacrificial layers were demonstrated in 1987 [54]. For surface micromachining, sacrificial layers are essential. Sacrificial layers are only used temporarily to build up a structure and are then etched off when the structure is defined. In silicon, the most common techniques build up polysilicon structures with silicon dioxide or phosphours glass as sacrificial layers. It is also possible to produce single crystalline structures, using SIMOX [55] or bonding [56] techniques. No surface micromachining has been found in quartz.

In GaAs, there are a number of different possibilities of sacrificial etching: In the $GaAs/Al_xGa_{1-x}As$ system the AlGaAs will etch selectively in contact with HF. With aluminum contents above 0.5, the etch selectivity is increased enormously and may be as high as 10^8 [35,36] (which is much higher than the selectivity of the polysilicon/silicon dioxide system). Recently, this system has been used to show surface micromachined laterally movable structures in GaAs [42,57]. Two other possible sacrificial layer techniques have been presented. With deep implantation of nitrogen and subsequent annealing, $GaAs_{1-x}N_x$ is created and may then be selectively etched in alkaline etchants [58]. It is also possible to use GaAs as a sacrificial layer leaving the unetched AlGaAs standing free, either by wet [59] or dry [60] etching.

Also, it is of course possible to do surface micromachined structures in other materials systems on top of GaAs. For example the techniques for air-bridges may be used to form complex surface micromechanics [61,62].

Solid-state bonding

Solid-state bonding is an important tool in silicon micromechanics, as a fabrication process free of "glues", with advantages of meeting close tolerances of interface thicknesses and with no flow of foreign material due to bonding.

In silicon, there are two major techniques: Electrostatic, field-assisted bonding combines an electrostatic force with elevated temperatures to make an (electro-)chemical surface reaction [63,64]. Direct bonding is making use of the spontaneous adhesive force exhibited when two surfaces are brought into close contact. In the most commony used direct bonding technique, fusion bonding, a subsequent annealing step gives a stronger bond [65,66]. Bonding of quartz is not very common, but has been reported [67].

In GaAs, the known solid state bonding methods are closely related to those in silicon. Field assisted bonding has only been reported with glass as one of the wafers to be bonded. The originators of field assisted bonding, Wallis and Pomerantz, claimed to have bonded GaAs successfully to glass, but without any descriptions [63]. Later, to create a strong bond to glass the need to remove the oxides from the GaAs surface and afterwards making the bonding in reducing atmosphere has been demonstrated [68]. No reports on field assisted bonding with thin deposited layers of glass or silicon dioxide have been found for GaAs, cf. those for silicon [69]. In future this would be an interesting possibility, since it may take away the need of a reducing atmosphere at the bonding step. Direct bonding has been done in at least three different ways: In the epitaxial lift-off technique with just the electrostatic bonding between thin epitaxial layers on glass- or silicon dioxide-covered silicon wafers [70,71]. High-temperature fusion bonding has been done at epitaxial temperatures with GaAs wafers freed from oxides [72]. Recently, low temperature fusion bonding was made in reducing atmosphere with GaAs wafers covered by a thick oxide layer. At 400 °C, the oxides are reduced, and the Ga and As seem to regrow to their surfaces. After the annealing, the bonds show high strength and only a very thin oxide layer between the wafers [73]. Here, as with solid state boding in general, very much is needed to be done for GaAs.

To summarize, GaAs lags far behind silicon in solid state bonding, but not much may be needed to make it come up at side. For fabrication of micromechanics in GaAs, this is one of the most urgent matters.

To close the micromachining section, it may be concluded that most of what can be done in silicon can also be micromachined in GaAs. In some cases, GaAs gives even larger opportunities of combination. A disturbing fact in some micromechanical applications is the problems of the inverse mesas in, e.g. membrane etching. For a more detailed description of GaAs micromachining, see [42].

Micromechanical Devices

Adding to the comparisons above, the matter of costs should be briefly mentioned before further discussions. Bulk GaAs is much more expensive than silicon, and GaAs micromechanics often need costly epitaxial layers. This makes low prized consumer products for large volumes difficult to achieve. GaAs micromechanics should, at least in a beginning, be used in more special applications.

In this section the driving and sensing principles will be discussed together with examples of realized devices. For most sensor applications in micromechanics stress, temperature, or displacement sensitive principles are used. For actuating structures most often electrostatic forces are used, but other means are also used like piezoelectric, thermal or electromagnetic forces. This section will in more detail compare the opportunities of GaAs and AlGaAs with silicon and quartz. Of course, there are as many different device solutions as the imagination accepts. This section will only describe the principles with a few references as examples.

The change of stress may be a measure for several physical qualities such as pressure, acceleration, and weight. For GaAs and AlGaAs four different sensing principles may be used: piezoelectric, piezooptic, piezoresistive or resonant. The resonant motion may be actuated optically and piezoelectrically, as well as electrostatically. In silicon the piezoelectric actuation is not possible, resulting in a smaller variety of vibration modes and often with rather a high damping and a low Q-factor (i.e. the ratio of the resonance frequency of the resonant peak to its width at half its maximum intensity). For quartz only piezoelectric resonant structures are used. GaAs and AlGaAs may also be used with piezoelectric actuation, with piezoelectric coefficients and possible semi-insulating qualities. Compared to quartz the piezoelectric coefficients of GaAs and $Al_xGa_{1-x}As$ are smaller, but they may have the driving and sensing electronics on the same chip as the resonant structure, enabling more sensitive measurements. Also, GaAs has the extra possibility of high-frequency resonance by optical excitation [59,74]. Here, the optically excited structure use a laser to drive the structure and a photodiode to measure the movement. Resonant vibrations as high as 1.006 MHz have been achieved.

For silicon the piezoresistive principle is the most often used, with stress sensitivities about 50 to 100 % per GPa. AlGaAs may have possibilities in its large piezoresistive response, with the pressure response of the DX deep level electron freezing in silicon doped material as one of the most interesting (resistivity changes as high as 400%/GPa) [75]. Also, some of the piezoresistive response mechanisms in AlGaAs do not need a change of symmetry, giving high pressure sensors without membranes [75,76].

In GaAs, the piezoelectric effect may also be used in static measure of stress. This has been demonstrated i two different ways: One using the piezoelectric effect directly [77,78], and one making the high-gradient induced bound charges to change the resistivity of a diffused resistor [79].

Compared to silicon, GaAs and AlGaAs have about the same high piezooptic response [80], demonstrated in very sensitive pressure sensors [81,82].

The temperature is an interesting physical quality by itself, but the change of it may also be used in the measurements of, e.g. flow or low pressures. In micromechanical applications, most often temperature

dependence is a disturbing quality, since it affects the measurements of other physical qualities. In the GaAs/AlGaAs system, temperature may be measured by, e.g., the change in photoluminescence, resonance, resistance, or the voltage change over thermopiles due to the change in temperature difference (i.e. the Seebeck effect).

The shift in photoluminescence for GaAs has been used in a simple fibreoptic temperature sensor [83]. Resonant thermometers in quartz are some of the most precise temperature sensors possible, due to the stability of the material and the high Q-factor possible to obtain by piezoelectric means [84]. Though not as stable, resonant micromechanics in GaAs and AlGaAs might be used with advantages in some applications where temperature is one of the measurements. For the cubic materials GaAs and silicon, the frequency responses to temperature are fairly constant to the crystal orientation, about -48 to -59 and -42 to -45 ppm/K, respectively [1]. As for silicon, the large change of resonance frequency with temperature has to be calibrated for in other sensor applications. In this aspect quartz is superior to the others, since it is also possible to use resonant directions in it with an extremely low temperature sensitivity (used in, e.g. quartz resonators in oscillator circuits for time reference). There are microprocessor compensated quartz resonators on the market with a frequency stability of 0.3 ppm over the full temperature range, including one year of aging [85].

The thermoresistivity response in GaAs may be very high. In undoped and Cr-compensated semi-insulating material, with increased temperature the resistivity drops by 8 and 6 % per °C, respectively [1]. For piezoelectric devices, this will lead to a degeneration at high temperatures. Also, the temperature dependence of DX deep levels in silicon doped AlGaAs may be in the same order of magnitude, and may also be changed by choosing the right doping [78]. Ordinarily doped GaAs and AlGaAs has a thermoresistive response about 0.1 % per °C. This may be supressed by one order of magnitude, choosing the right doping concentration for the temperature interval of interest [79].

Depending on doping and aluminum concentration, the Seebeck coefficient for $Al_xGa_{1-x}As$ will be up to 0.8 mV/K, with a rapid increase from the aluminum contents of 0.3 to the maximum at 0.45 [86].

Although most often a problem in electronics, in some sensor applications the high thermal resistance (W) of $Al_xGa_{1-x}As$ ($W = 2.27 + 28.83x - 30x^2$ cmK/W at room temperature [2]) may be used with advantage. The maximum thermal resistivity (9.2 cm K/W at an aluminum contents of 0.48) is more than 14 times higher than that of silicon, and is increasing rapidly with temperature. This feature has been used in an anemometer (gasflow sensor) in combination with Seebeck thermopiles [87]. The results are most promising, and the thermal resistivity could also be used in combination with other sensing principles.

The displacement sensitive principles most commonly used in micromechanics are capacitive, interferometric, or simply measuring the change of light intensity. In silicon and quartz micromechanics capacitive pressure sensors [88] and accelerometers [9,89] are used for highly sensitive applications. The change in the degree of reflection have been used for deflecting structures, e.g. in pressure sensors. Also, interferometric structures have been used with good results in silicon micromachining, using e.g. a Fabry-Perot cavity [90]. One fibreoptic GaAs accelerometer has been presented, working with the light intensity change and using the photoluminescent intensity as a scaling signal [83].

In GaAs three actuating principles have been used, though most of the microactuators in silicon are also possible to realize. In surface micromachined structures, capacitive forces [42,91] have been used. The capacitive structures are very close to what previously has been done in silicon, with elastically suspended capacitive structures moving with the change of voltage. In bulk micromachined structures, piezoelectric resonators have been achieved [92,93]. All these actuating principles have the large limitation that they only manage to drive the actuating structure itself, either the forces or the movements are to small to make a micomechanical motor out of them.

One last item of interest for applications in GaAs micromechanics may be mentioned: The ability of GaAs to be semiconducting at higher temperatures than silicon, due to the larger bandgap. GaAs-based electronics have been realized for temperatures up to at least 350 °C [94,95]. This may enable high-temperature sensors, using semiconducting sensing principles or integrated circuitry. But, even more interesting devices based on the specific properties of GaAs can be envisaged, the optoelectric and piezoelectric properties combined, for instance. This combination may facilitate an optically driven piezoelectric movement. Maybe even micromotors could be driven just by the light shining on them. However, this visionary motor concept still remains to be realized and may serve more as an illustration of the possibilities that may lie in III-V physics for micromechanics.

Conclusions

Comparing GaAs with silicon and quartz, it is seen that GaAs combines the advantages of both silicon and quartz. Like silicon, it is semiconducting and it is possible to do advanced micromachining in GaAs. Like quartz, it is piezoelectric and may have a very high bulk resistivity. Also, with GaAs come new possibilities in integrated optoelectronics, such as lasers and photodiodes.

It is shown that most of what can be micromachined in silicon can also be made in GaAs. In some cases, GaAs gives even larger opportunities of combinations. Also, the mechanical characteristics of micromechanical structures of

GaAs are sufficient to make it a good micromechanical construction material.

The main advantages of silicon are: it has a better mechanical endurance, it is cheaper, and it is the mostly used material in micromechanics. The large advantages of quartz are: an extreme stability, it is a truly insulating material, and it is possible to obtain resonant vibrations with little temperature drift. Compared to silicon GaAs has advantages in the possibility of semiconducting performance at high temperatures, and its optoelectrical and piezoelectric properties. Also, a higher stress sensitivity, a high thermal resistivity, and twice the density may be used to advantage. Compared to quartz, GaAs has the large advantages of being semiconducting, optoelectronic, and that it may be micromachined in almost the same ways as silicon.

As mentioned before, there are no reasons to introduce a new technology if the existing one is sufficient. Therefore, sensor and actuator applications should take advantage of those special opportunities GaAs offers. This make some sensor areas of special interest for further studies: Piezoelectrically driven resonant sensors with integrated electronic; sensors making use of the semiconducting properties at high temperature; and sensors using some of the optoelectronic properties of GaAs. Actuator applications could be surface micromachined nanopositioning systems, mechanically movable filters, shutters, or choppers, monolithically integrated with GaAs optoelectronics; or movable structures for variable capacitances or switches in MMIC's. One application which could be of special interest is resonators in GaAs with monolithically integrated electronics.

It is concluded that GaAs based micromechanics has a large unexploited potential. It is conceivable that GaAs may assume the same position in micromechanics as it already has done in microelectronics.

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